ARTICLE IN PRESS

Composite Structures xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Quasi-static and dynamic compression behavior of glass cenospheres/5A03 syntactic foam and its sandwich structure

Qiang Zhang *, Yingfei Lin, Haitao Chi, Jing Chang, Gaohui Wu

School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Article history:
Received 18 January 2017
Revised 9 May 2017
Accepted 11 May 2017
Available online xxxx

Keywords:
Composite
Aluminum matrix syntactic foam
Dynamic compression behavior
Sandwich structure

ABSTRACT

5A03 aluminum matrix syntactic foam filled with glass cenospheres was synthesized using pressure infiltration technique. This paper focused on the compression behavior of syntactic foam at quasi-static (10^{-3} s^{-1}) and dynamic (strain rate 1×10^3 s^{-1}–3×10^3 s^{-1}) condition, and the dynamic response of syntactic foam core sandwich structure with two different wave impedance front-panels (A3 steel and AZ31) subjected to split-Hopkinson pressure bar. The syntactic foam at dynamic loading exhibited a maximum 43% increase in peak strength, 38% in plateau strength, and 23% in energy absorption capacity compared to quasi-static results, with 0.03 strain rate sensitivity similar to that of aluminum matrix. The dynamic compression behavior can be concluded as thin near-45° shear bands forming, deformed area propagating to the central and lateral parts, and finally densifying with significant lateral expansion. The sandwich structure exhibited great energy absorption capability due to the syntactic foam core. The higher wave impedance front-panel would be conducive to the energy absorption capability of syntactic foam core into full play.

1. Introduction

Cellular metallic materials (foams, honeycombs and lattices) have positive combinations of physical and mechanical properties, such as high specific stiffness and strength, excellent plastic energy absorption capacity, good corrosion resistance and gas permeability, as well as high damping properties [1,2]. Their cellular microstructure endows them with the ability to undergo large strain deformation at a relatively constant stress, and they are often considered to be ideal energy absorber for usage in packaging applications or impact protection [3,4]. Common uses of cellular metals include light weight cores for sandwich structures, with strong and stiff faces-sheets, to enhance shock resistance. These structures can be used in automobile, aerospace, building structures, and armor for both military and civil uses [5–7]. In recent years, engineers have investigated the energy-absorbing characteristics of sandwich structures subjected to a wide range of loading conditions [8–11]. The mechanical response of a sandwich structure is largely dependent on many parameters, including the properties of the skin, the stiffness and strength properties of the core, the wave impedance ratio and the thickness ratio the between the core and skin and so on [12–16]. The need to strengthen the core and understand its crushing characteristics is essential to maximizing energy absorption in sandwich structure.

Aluminum foam, as a typical cellular metal, has the potential use in energy absorption sandwich core. From the scientific point of view, many researchers have engaged in the investigation of the dynamic compression of Al foams and their sandwich structure [6,17–20]. Gama et al. [6] proposed that Al foam could be a positive idea for the use in integral system design. Cady et al. [17] systematically evaluated the dynamic compression of aluminum foam (ALPORAS) using a split-Hopkinson pressure bar (SHPB). Styles et al. [18] investigated the effect of core thickness on the deformation mechanism of an aluminum foam core sandwich structure under 4-point bending. Mohan et al. [19] studied the impact responses of aluminum foams with various tailored face sheets using hemispherical indenters. Jing et al. [20] examined the deformation/failure modes and blast resistance of sandwich structure comprising an aluminum foam core and two aluminum face-sheets subjected to air blast loading. However, the low strength of Al foam is somehow difficult to meet the need of application requirement.

Aluminum matrix syntactic foam (AMSF) is a typical novel cellular composite material synthesized by aluminum alloy filling with hollow particles (SiC hollow spheres [21], fly ash [22,23], and Al_2O_3 microspheres [24,25], etc.). Compared to the Al foam, the mechanical properties and energy absorption of the syntactic

* Corresponding author.
E-mail address: zhang_tsiang@hit.edu.cn (Q. Zhang).

http://dx.doi.org/10.1016/j.compstruct.2017.05.024
0263-8223/

Please cite this article in press as: Zhang Q et al. Quasi-static and dynamic compression behavior of glass cenospheres/5A03 syntactic foam and its sandwich structure. Compos Struct (2017), http://dx.doi.org/10.1016/j.compstruct.2017.05.024

foam can be improved due to the existence of hollow particles [26,27]. Generally, the impact performance of high strain rate is the key feature to the energy-absorbing components [28,29]. In order to evaluate the impact behavior of the potential energy absorber candidate AMSF, many investigators have involved into the research of various AMSFs using a split-Hopkinson pressure bar. Balch et al. [30] examined the dynamic compressive properties of commercial pure Al syntactic foam and 7075 syntactic foam. The dynamic compression loading showed a 10–30% increase in peak strength magnitude compared to quasi-static compression and the strain rate sensitivity of the foam is significantly controlled by the strength of the matrix. Goel et al. [31] studied the compression behavior of aluminum cenosphere syntactic foam for strain rates ranging from quasi-static to 1400/s. The results also exhibited that the syntactic foam had about 10–30% high dynamic compressive strength than that of quasi-static condition. They indicated that the compressive strength and energy absorption capacity of foams would reach to the maximum at a critical strain rate. They also found that the foam with coarser cenospheres appeared to be more strain rate sensitive. Luong et al. [21] investigated the dynamic properties of SiC hollow sphere/A356 syntactic foam, but the foams didn't show strong evidence of strain rate sensitivity within the high strain rate regime. Maria et al. [32] also found that the properties of Al_2O_3 hollow sphere/A380 syntactic foams containing 0.425–0.85 to 0.85–1 mm diameter hollow spheres were not strain rate-dependent. Myers et al. [29] demonstrated that the compressive strength of ceramic hollow spheres/Al (Al99.5, AlSi12, AlMgSi1 and AlCu5) syntactic foams showed limited sensitivity to the strain rate. In addition, the failure mode of foams would change due to the restricting effects of the material during the sudden loading under high loading rates. Zou et al. [33] investigated the dynamic compression of fly ash/6061Al syntactic foam and designed a sandwich structure with syntactic foam core. Omar et al. [34] showed the compression of Al_2O_3 hollow sphere syntactic foam core sandwich at high strain rate and found that the failure characteristics were similar at all high strain rates (525–845/s).

All the studies above reveal useful information about the dynamic compressive properties of specific Al matrix syntactic foams. The sensitivity to the strain rate for various AMSFs is different due to the strength of the matrix, the size of hollow sphere, and the strain rate. However, the investigation about the design of syntactic foam core sandwich structure is limited. Thin, high-strength steel plates are often applied in civil and military ballistic protection systems in the form of monolithic or layered [35,36]. A3 steel is a carbon structural steel with about 0.2 wt% carbon content, it has a variety of industrial application due to its good mechanical properties, plasticity as well as weldability, as a result, it is suitable for use as front-panel or back-panel in the study of ballistic resistance or energy absorption structures [33,37]. AZ31 is a widely used magnesium alloy in many applications such as automotive, aerospace, and defence systems due to its lightweight, good ductility and impact toughness, as well as energy absorption at high strain rate [38,39]. For double-layered structure by using steel and aluminum, steel-aluminum style would absorb more energy rather than aluminum-steel [40]. Therefore, A3 steel and AZ31 have been determined as front-panels for sandwich structure in this work. The corresponding double-layered structure without syntactic foam core, A3 steel-aluminum and AZ31-aluminum, are also considered to better understand the energy absorption capacity of the syntactic foam in sandwich structure. The aim of the present paper is to extend the available comprehensive data regarding the quasi-static and dynamic compressive properties of glass cenosphere/Al syntactic foam, and to qualitatively evaluate the effect of front-panel on the energy absorption capacity of sandwich structure with syntactic foam core for better designing energy absorption component.

2. Materials and experiment

In this study, syntactic foam composed of aluminum alloy 5A03 reinforced with glass cenospheres (3M Company, S38 Glass Bubble) was synthesized through pressure infiltration technique. The nominal compositions of alloy and the glass cenospheres provided by suppliers are presented in Table 1. The cenopsheres were of amorphous structure with a large amount of SiO_2 [41]. The size distribution and material properties of cenospheres provided by manufacturer are listed in Table 2. The cenospheres showed a good supporting capacity with high porosity, making them suitable as fillers for the synthesis of aluminum matrix syntactic foams.

A schematic diagram of the pressure infiltration technique used for synthesizing Al matrix syntactic foam is shown in Fig. 1, and the fabrication process steps were summarized as: (1) Melting Al matrix alloy – 5A03 alloy was molten in the chamber and kept at 850 °C; (2) Preparing preform – Cenospheres were filled in a steel mold with a vertical pressure of ~0.5 MPa as a cylindrical preform, and then was preheated at 600 °C for 2 h; (3) Synthesis – Molten aluminum was infiltrated into the preform with a pressurization equipment and (4) Solidification – Maintaining a packing pressure of ~0.8 MPa for 5 min until the syntactic foam solidified completely. All fabrication processes were carried out in ambient air. Specimens for investigation were cut using electrical discharge machining (EDM) from as-cast composites and annealed at 325 °C for 30 min for eliminating residual stress.

The density of the composites was measured using a BP211D-0CE (Satorius AG) microbalance equipped with a density measurement apparatus (Archimedes principle). Metallographic samples for microstructural analysis, related to the compression behavior under quasi-static and high strain rates condition, were polished using SiC paper, followed by 1 μm water-based diamond suspensions, and examined by optical microscopy (ZEISS-40MAT).

Quasi-static compression testing was performed in accordance with DIN 50134 standard on cylindrical specimens with 8 mm diameter and 12 mm length. Testing was carried out using Instron 5569 Universal Testing Machine at constant crosshead speed with an initial strain rate of 10^{-3} s^{-1}. The surface of the specimens were experienced mechanical polishing before testing and were lubricated with MoS_2 lubricant for reducing the friction between specimen surface and compression test plant. For foams, the quasi-static compression curves typically exhibited an initial peak followed by a large strain deformation at a relatively constant stress and later densification. As a result, compression testing in this work was stopped after the densification strain, which was approximately 70% strain.

Table 1
Nominal composition of matrix and cenosphere.

Material	Component	Nominal content, wt%
5A03	Al	94.9
	Mg	3.2
	Si	0.6
	Mn	0.5
	Fe	0.4
	Zn	0.2
	Ti	0.1
	Cu	0.1
Glass cenosphere	SiO_2	77.8
	CaO	14.2
	Na_2O	6.4
	MgO	0.2
	Al_2O_3	0.1
	P_2O_5	0.8
	SO_3	0.3
	LOI[a]	0.2

[a] Loss on ignition.